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TECHNICAL EVALUATION REPORT ON THE FLIGHT MECHANICS PANEL SYMPO--ETC(U)
JAN 79 C R CHALK

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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

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AGARD ADVISORY REPORT No. 134
Technical Evaluation Report
on the
Flight Mechanics Panel Symposium
on
Stability and Control

by
C.R.Chalk



NORTH ATLANTIC TREATY ORGANIZATION



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NORTH ATLANTIC TREATY ORGANIZATION
ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT
(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

9 AGARD Advisory Report No. 134

6 TECHNICAL EVALUATION REPORT

on the

FLIGHT MECHANICS PANEL SYMPOSIUM

on

STABILITY AND CONTROL

by

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TECHNICAL EVALUATION REPORT
ON THE
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1. INTRODUCTION

The Symposium was held at the Government Conference Center, Ottawa, Canada, September 25-28, 1978. Approximately 115 attendees from ten NATO countries registered at the Symposium, most of them attending through the four days.

The theme of the Symposium was stated in the meeting announcement as follows:

"The design of aircraft has always been closely constrained by the need to comply with stability and control requirements. The developments in automated control systems, however, have radically changed this outlook by introducing artificial stability augmentation. The technology of designing these systems has been labeled Active Control Technology (ACT) and vehicles utilizing ACT have been called CCV's. Since aircraft can obviously be designed to benefit greatly from the use of these developing techniques, this symposium will seek to examine some of the possibilities for matching control systems and characteristics to aircraft mission requirements. It is intended that emphasis will be placed, not on control systems design, but on the more fundamental relationship between the use of advanced CCV concepts and appropriate aircraft design."

Conference Proceedings will be published under the normal schedule. The purpose of this report is to present a comprehensive review and evaluation of this technical meeting and to formulate conclusions and recommendations based on the information presented at the Symposium.

2. SUMMARY AND EVALUATION OF SYMPOSIUM

The Symposium was arranged in six sessions covering the technical areas identified by sections 2.1 through 2.6 in the Table of Contents. The total of twenty-six papers was reasonably distributed over the contributing countries (USA and Canada: 35%; Europe: 65%). A final Round Table discussion addressed problems that may impede full implementation of ACT. A resume of the main points of each session, as perceived by the author of this Technical Evaluation Report, is presented on the following pages.

2.1 Summary of Recent Experiences in Stability and Control

The four papers presented were of a survey nature. The first was a comprehensive review of seven ACT applications to aircraft in the United States. The paper pointed out the promise of increased aircraft performance and operational capability that ACT offers when considered from the beginning of the design process. Realization of these gains may require departure from existing design practice in the direction of decreased static aerodynamic stability, increased control authority for automatic control systems, increased dynamic bandwidth of control servos and reduced structural strength and stiffness. The overall success of ACT therefore becomes dependent on ability to handle failure modes and to provide cost effective reliability and maintainability. The use of ACT to reduce dynamic structural loads and to stabilize structural modes will involve an unprecedented understanding of the anticipated external disturbances, aerodynamic and structural characteristics, control system responses and compatibility problems and will require considerable advances in our ability to describe and model such phenomena. Work remains to be done before structural dynamic and aerodynamic models can be used with confidence in the initial CCV configuration selection. This situation gives emphasis to development of control approaches that are parameter-insensitive which can deal with errors in predicted aircraft parameters.

It was pointed out that very high reliability, i.e. 10^{-9} , need only be required for a few critical ACT functions such as flutter control and extreme basic instability. Discussion from the floor emphasized that ACT technology is available but we should avoid doing the attainable just because we can unless there really is a benefit. It was noted that some benefits can be calculated, but when the pilot is involved, there are questions as to how handling qualities should be specified.

The second and third papers were reviews of two recent AGARD Conferences held in Athens and Lisbon which dealt with Dynamic Stability Parameters, AGARD CP235, and Structural Aspects of Active Controls, AGARD CP228. The review of CP235 emphasized the papers dealing with wind tunnel testing at high angle of attack and sideslip where the aerodynamic forces and moments are affected by flow separation and exhibit nonlinearities and discontinuities which are very configuration sensitive. Since the high angle of attack characteristics are dominated by separated flow effects, they are very dependent upon Reynolds number and boundary layer phenomena. The interference effects of captive model support structures can become large at high angle of attack because of the effect of downstream supports on separated flow vortices and wakes. Support interference can have large effects on both static and dynamic aerodynamic characteristics of the

model. The separation-induced aerodynamic forces affect static and dynamic stability in opposite ways, i.e., the effect can be statically stabilizing and dynamically destabilizing or the other way around. Which it is depends on configuration details.

Because there are many problem areas involved in high angle of attack wind tunnel testing, there is a need for further investigation of these problems and for development of communication channels between wind tunnel test engineers, analysts, flight test engineers and parameter identification specialists which will facilitate information flow and the inter-disciplinary dialogue that will be necessary to identify problems and develop solutions.

The reviewer of CP228 pointed out that the subject can be addressed by dividing it into three frequency bands. The low frequency region deals with flying qualities and rigid body motions; the intermediate frequency region deals with maneuver loads, gust loads and aerodynamic buffet; the higher frequency region deals with structural modes and flutter. A general design approach consisting of three phases was advocated. The first step is based on simplified theories assuming exact parameter knowledge. Next, through wind tunnel test and measured data, the theory is rectified and the design is modified. The final stage is to flight test and to use the results to further modify and develop the theory.

In addition to reviewing the papers in CP228, the third speaker described an active control system designed to stabilize the flutter mode of a wing store combination of a fighter aircraft. The design was carried through dynamic wind tunnel tests which demonstrated flutter and elimination of flutter by alternately deactivating and activating the active control system during the wind tunnel test.

The fourth presentation outlined the techniques used in missile airframe control systems. The range of speeds and accelerations encountered in missiles has, in the past, been more severe than for manned aircraft but as the performance of manned aircraft increases and the missile technology diversifies to include remotely piloted vehicles and cruise missiles, the stability and control problems are now more closely allied. The airframe designer, however, must always bear in mind the requirements of the pilot and because aircraft are larger, more expensive and manned, they must be designed with very high levels of safety and reliability which often leads to duplication of equipment. This is not usually the case in missile design where it may be cheaper to use two cheap missiles to accomplish a job rather than one expensive weapon.

The missile designer has had to design for very high longitudinal and normal acceleration levels and very large dynamic pressure and Mach No. ranges. These performance factors require relatively high dynamic bandwidth in the control system and close attention to choice of sensors and their location in the vehicle to avoid structural interaction, dynamic instability, and sensitivity to noise disturbances or aerodynamic variations.

In summary, the missile designers have been dealing with many of the active control design problems now worrying aircraft designers and much of the missile experience is applicable to the aircraft design application. The requirements for safety and reliability and life cycle cost are significantly different, however, and may have a dominant influence in determining the role ACT will play in future aircraft design.

2.2 Application of Active Controls to Specific Aircraft and Aircraft Systems

This session consisted of three presentations, two of which described design studies and ground simulation studies of the application of ACT and CCV concepts to fighter aircraft design. The third paper described development and flight test of a fly-by-wire control system for the Concorde supersonic transport with relaxed static stability, i.e., aft center of gravity.

The fighter design studies attempted to quantify performance advantages and operational advantages of CCV and ACT concepts. Concepts investigated include relaxed static stability, use of active control to meet flying qualities requirements, exploration of direct force control from flaps and sideforce surfaces and the advantages of a trainable gun in air-air and air-ground gun attack. Simulation studies indicate significant operational advantages resulting from automatic integrated flight control and fire control systems but the paper does not evaluate whether or not the increases in effectiveness of the fuselage-pointing and/or gun-pointing features over the basic integrated flight/fire control system are sufficient to warrant the cost of their incorporation.

Conclusions resulting from the fighter design studies are that the CCV concept of negative longitudinal static stability and the use of full authority active controls to provide dynamic stability and departure prevention can provide very large improvements in combat performance in terms of sustained turn rates, lower gross weights and extended combat range. These design trends require high reliability in the flight control system. The current approach to achievement of reliability is through redundancy and redundancy management logic and the digital computer is attractive as a major component in these flight control systems.

When requirements for natural stability are relaxed and dependence is placed on ACT, then it is imperative that adequate control power be provided to handle all circumstances of large amplitude maneuvers, external disturbances and special maneuvers required to demonstrate structural integrity. In addition, adequate control surface rate, hinge moment capability and dynamic bandwidth must be provided to ensure the system can provide the flying qualities and maneuver capability the pilot requires.

The paper reporting on the Concorde fly-by-wire experiments resulted in several observations and results of general interest. The system used a side stick located on the left side of the cockpit. The pilots involved had no difficulty adapting to left hand operation but it was concluded that stick displacement was a needed feature of the hand controller.

The use of an integral path in the forward loop of the longitudinal control system, which used pitch rate and normal acceleration feedback, resulted in undesirable characteristics during flare for landing. This situation was improved by elimination of the integral path.

Closed-loop oscillations involving a fuselage structural mode were encountered when the aircraft was on the ground. This required changing system gains when on the ground.

2.3 General Problems Concerning Stability and Control and Associated Mathematical Models

Eight papers were presented in this session dealing with a variety of subjects. Two papers were concerned with lateral-directional stability at high angle of attack. Two were computer studies involving the effects of discrete gusts, windshear and downdraughts on aircraft responses and effects on automatic landing system performance. Two papers described work relating to the use of active control systems for gust alleviation. One paper reviewed various design considerations for reliable fly-by-wire flight control systems. Paper No. 16 was classified NATO-restricted and will not be reviewed in this Technical Evaluation Report.

Two papers reported on development of nonlinear analytical models of lateral-directional aerodynamic characteristics at high angle of attack that were successful in calculating dynamic behavior measured from flight test of full scale aircraft. Paper No. 10 reported good success in modeling the wing rock motions of the Gnat aircraft through use of nonlinear variation of roll damping as a function of roll rate magnitude and nonlinear variation of rolling and yawing moments due to sideslip as a function of the magnitude of the sideslip angle. The nonlinear functions are cubic in degree. The work shows that the wing rock phenomena can be explained in terms of nonlinear variations of familiar parameters. This paper is a very good example of the application of parameter identification methods to flight data using a mathematical model that is based on the physics of the situation.

The second paper dealing with stall effects on lateral-directional dynamics concluded that random fluctuations of rolling and yawing moments and lift coefficient resulting from flow separation were responsible for discrepancies between flight test recorded motions and motions experienced in the ground simulator. It was necessary to account for the random fluctuation moments before behavior of the ground simulator was similar to the flight test. Therefore, it is necessary to measure the time variation of wind tunnel moments and not just the steady state or time average values. The maximum fluctuation magnitudes are adequate to permit calculation of the aircraft lateral-directional behavior at stall using a simple pilot model for roll control. It was noted that the longitudinal motions are essentially independent of lateral motions but the lateral-directional motions are dependent through the angle of attack effect on lateral-directional derivatives.

Paper No. 12 reported on studies done during certification of the autoland system for Concorde. This study showed that the power spectral density turbulence model was not adequate because it is too severe on average turbulence and moreover is no good for specific gust patterns that are critical for autoland system performance. A discrete gust modeling method was developed which permitted modeling specific gust shapes and locations which were found to correlate with hard, short, and long landings. The question of permitting the use of computer models and piloted simulation in the certification of civil aircraft was raised in the discussion. The position of the U.S. FAA was stated to be that computer analysis would be accepted for exploration of limits but would not be accepted as the final answer. It was stated that the FAA is exploring the use of piloted simulation in the certification process.

Paper No. 13 also addressed the problem of modeling low altitude random atmospheric turbulence and variations of mean wind with altitude. An analytical method to find deterministic wind or turbulence time histories, referred to as "worst case," that cause the largest deviations of aircraft motion variables was described and illustrated. These "worst case" time histories are not general characteristics of the atmosphere but are specific to each aircraft and the control law driving its control surfaces. There is, therefore, a problem of how to scale these worst case time histories such that they represent likely magnitudes that might be experienced in flight. It was noted that specific wind shears associated with airline accidents were not "worst case" examples. These kinds of accidents could be avoided if correct action is taken in controlling the aircraft. From the point of view both of automatic landing system design and certification and of timely "pilot reporting" a collection of windshear data under actual operational conditions (in the aircraft itself) could be of considerable value.

Paper No. 14 described a gust alleviation system designed for the G91Y tactical fighter. The system used a roll damper and an open loop longitudinal gust relief system that actuated the elevator and flap control surfaces. A primary part of the system was a computer to estimate the gust velocity signal that used airspeed, normal acceleration and pitch attitude as inputs.

Paper No. 15 was a discussion of experience gained in the USAF "Survivable Flight Control System Program" which relates to design of high authority fly-by-wire flight control systems. The primary value of this and other similar projects involving flight control design, construction and flight test is to gain hands-on experience and to develop the necessary analysis and design tools. A further objective of the projects sponsored by the USAF has been to develop confidence in and to promote acceptance of the concept of full authority fly-by-wire flight control systems. These programs have established a technology base for application of ACT. The current need is for highly reliable/fault-tolerant flight control system mechanizations. There was concern expressed over the vulnerability of electronic flight control systems to electrical discharge and electromagnetic interference. This concern is heightened for aircraft employing composite structural materials and digital electronic flight controls.

During the question period, comment was made that it could be important to differentiate between stable and unstable aircraft when making reliability analysis. The consequences of a failure in an unstable aircraft could be more severe — even catastrophic. For example, an ejection seat could save the pilot in a stable aircraft whose control system failed, but might not be adequate on an unstable aircraft with a similar failure.

Paper No. 16A was added to the program at a late date and was not included on the program printed schedule. The title was "Dynamic Wind Tunnel Simulation of Active Control Systems" by P. Hamel and B. Krag, DFVLR. This paper described the research studies performed by DFVLR to demonstrate the application

potential of the "Dynamic Simulation in Wind Tunnels" test facility. Elastic mode control and ride smoothing systems were scaled to model frequency and tested in the DFVLR 3-meter subsonic gust wind tunnel. An open-loop, active-control, ride-smoothing system was optimized for the Dornier-TNT light transport aircraft in an experimental program. Movie film was shown of dynamic tests in the gust tunnel which illustrated operation of the gust generation system and "flight" of the model in limited degrees of freedom under the influence of active controls. This is an impressive facility which should permit dynamic testing of ACT concepts in a controlled environment that permits observation of all states and disturbance variables which act on the model. The capabilities of the facility are detailed in the paper together with many research applications for which it has been used and for which there are future plans.

2.4 Results Obtained With CCV's

Five papers were presented in this session. Two discussed CCV modifications to existing fighters, the F-104 and the YF-16 aircraft. The F-104 airplane was modified by the addition of a fixed canard to move the aerodynamic center forward and by the addition of aft ballast to move the center of gravity aft so as to produce a statically unstable configuration. The aircraft does not have any direct force control surfaces; only moment controls are available. The project is a hands-on exercise to develop the experience and technology necessary to design redundant, full-authority, fly-by-wire flight control systems implemented using digital hardware. The system was designed to a two-fail operational requirement which dictated a quad redundant system.

The computer cycle time was quoted as 60 ms and the system includes low pass filters on the inputs to the surface servos. These characteristics prompted warnings from the representatives from the USA concerning the risk of pilot-induced oscillations, particularly during landing, based on in-flight experience with the NASA F-8 airplane equipped with a digital flight control system and experience with the USAF NT-33A variable stability airplane during flying qualities experiments.

Paper No. 18 described the CCV YF-16 airplane which includes vertical canard surfaces and wing flaperons for direct force control. Ballast and fuel transfer is used to move the center of gravity aft. The system used single channel command paths to command the vertical canards and flaperons. The surfaces were commanded open loop in all modes except the maneuver enhancement mode, which used a normal acceleration feedback to the flaperon. The system was configured to demonstrate pitch and yaw fuselage pointing, vertical and lateral translation, blended maneuver enhancement and gust alleviation.

Although paper No. 18 describes the control modes available in the CCV YF-16 and gives brief evaluations of their operational utility, the presenter stated that the CCV YF-16 was only a test bed to demonstrate feasibility and that it was not suitable for use in establishing the value of the new modes or to determine whether or not they are worth the cost. The most favorable application seemed to be in ground attack as a means for correcting aim errors without bank and for eliminating the gunsight pendulum effect. The direct side force capability was useful in trimming crosswind side force thereby permitting wings level sideslipping landings.

The author of paper No. 18 did not give much space in his paper to discussion of the aerodynamic interactions between the force and moment producers on a CCV design. These interactions can be prime factors in determining the viability of the unconventional control modes. In a movie demonstrating the control modes, it was evident that the yaw pointing mode had rather severe coupling or excitation of the Dutch roll mode. Flight tests also indicated a large increase in the horizontal tail deflection required to trim at high angle of attack when the flaperons were deflected -15° (up). This trim requirement would use full horizontal tail deflection at angles of attack greater than $\approx 24^\circ$. A previous paper, Reference 1, was presented at the AGARD Dynamic Stability Conference in Athens during May 1978. This paper discussed the aerodynamic interactions encountered in the CCV YF-16 program. The program demonstrated that the CCV concept, rather than reducing the importance of bare airframe aerodynamics, has resulted in an increased requirement for a thorough and accurate definition of aerodynamic characteristics. The control surfaces used to "decouple" aircraft motions and implement CCV concepts can be expected to exhibit nonlinearities and interference effects which should be accounted for in the design process. The closed-loop flight control system can compensate for some aerodynamic deficiencies, however, there are limits beyond which control system fixes of aerodynamic characteristics are not practical or possible. Future CCV designs may require an increased scope of wind tunnel testing in the form of larger parametric matrices to identify and solve adverse aerodynamic interaction and nonlinearity effects. Guidelines are needed to define acceptable levels of buffet and energy changes associated with decoupled control modes. An urgent need exists for development of appropriate flying qualities criteria.

Paper No. 19 described an in-flight experiment performed on a variable stability Navion aircraft to explore the use of direct side force during the approach and landing. Different command techniques were explored involving use of the aileron stick, rudder pedals, thumb-operated rate switch and thumb-operated spring-loaded lever. It was concluded that the stick and rudder pedals should be retained for their normal function and that an auxiliary controller be used to command the direct side force control mode. Although this test program and others performed in the USAF Total In-Flight Simulator have shown side force to be of advantage during crosswind landings, the question remains as to what practical means can be used to generate the side force in an operational aircraft. The variable stability aircraft was equipped with large vertical surfaces mounted on the wings.

Paper No. 20 reviewed the design philosophy used and experience gained from application of ACT to the Lockheed L-1011 transport. The L-1011 used a yaw stability augmentation system and an autoland system. The yaw SAS was used to reduce the fin design load by 20%. A recent research program funded by NASA under the Aircraft Energy Efficiency Program has demonstrated active controls performance in a wing load alleviation application for an extended span wing. The availability/reliability level used for this design is higher than that assumed for the yaw SAS fin analysis because years of experience with current systems have shown failure rates that are orders of magnitude less than originally assumed.

Flight test data from stall demonstrations have been employed to define a pitch control power criterion for use in preliminary design balance and tail sizing. This criterion is based on a survey of nearly 400 stall time histories from three aircraft in which pitch acceleration demanded during stall recovery was measured. This data was plotted vs. pitch inertia and it was found that a simple curve related the magnitude of pitch acceleration demanded by the pilot to the size or pitch inertia of the airplane. This criterion replaces static margin in setting an aft c.g. limit for a given tail size for relaxed static stability designs.

Lockheed's experience with flight and simulator testing of active control derivatives of the L-1011 allows two general conclusions to be stated by the author of paper No. 20.

- New criteria for active controls do not appear to be required. Existing criteria interpreted in terms of "equivalent safety" are satisfactory.
- An extensive data base is invaluable to the successful application of active controls.

Lockheed's approach to U.S. Federal Aviation Administration (FAA) Certification of active controls is to rely on the philosophy of equivalent safety as allowed by the Federal Aviation Regulations, Part 1. Under this philosophy, it is shown that the safety of the aircraft is equivalent to that of aircraft successfully certified within traditional deterministic criteria envelopes. In the application of this philosophy, much of the safety analysis is conducted using quantitative combined probability techniques. Probabilistic analysis accounts for system reliability in conjunction with exposure to predicted load or hazard levels.

Paper No. 21 described an experiment to investigate the effect of direct lift control and short period dynamics on longitudinal flying qualities for an altitude tracking task that is characteristic of wide-body transport ILS approach. The tests were performed in the DFVLR 320 variable stability aircraft used both as an in-flight and as a fixed-base ground simulator. This in-flight simulator operates on the model following principle, therefore, the dynamics to be evaluated are set up on the model computer. The pilot's control column commanded the model elevator surface and the model lift flap through first order filters or servo actuators. The elevator servo time constant was $T_M = 0.1$ sec and the flap servo time $T_{DLC} = 0.5$ sec. The experimental matrix was formed from combinations of the ratio of the command gain to the elevator and flap actuators, $K = \frac{K_{DLC}}{K_M}$ and the short period frequency. The heave damping was fixed at $Z_W = -.45$ and the short period damping ratio was fixed at $\zeta = 0.4$. This implies that the pitch damping was varied when the short period frequency was changed.

Although the $\frac{\theta}{s}$ transfer function resulting from the above described model is third order over sixth order, the authors of paper No. 21 chose to describe the experiment in terms of individual stability derivatives and response values at time "zero" and time "infinity".

This is an interesting experiment, however, the model parameters are not defined completely enough to permit evaluation or interpretation in terms of parameters other than those used by the authors, which this author finds inadequate.

2.5 Criteria for Satisfactory Behavior of Aircraft With Advanced Stability and Control Systems

Three papers were presented in this session. Paper No. 22 reported flight test experience with the Tornado flight control system and makes comparison of flight characteristics with the requirements of MIL-F-8785B. Paper No. 24 reports the results of a ground simulator experiment directed at investigating the minimum short period frequency and n_z/α boundaries in MIL-F-8785B for the Landing Flight Phase. Paper No. 23 asked the question "Are Today's Specifications Appropriate for Tomorrow's Airplanes?" and then argues that the answer is "Yes" if the method of "equivalent systems" is used to calculate the flying qualities parameters that are compared to the specification requirements.

Paper No. 22 is a rare example of a type of paper that should be encouraged. In this paper the airplane designer admits that his airplane, equipped though it is with a full authority fly-by-wire flight control system, turned out to have serious flying qualities problems that required solution. The example is rare not because problems occurred, but because the designer was willing to report on the experience. In fact, similar problems (pitch PIO in landing caused by control system phase shift and roll PIO caused by high roll control gain) have been experienced in highly augmented aircraft designed in the USA such as the YF-17, YF-16, F-18 and Space Shuttle.

The effect of control system lags and time delays on pilot-in-the-loop flying qualities has been explored in a number of experiments sponsored by the USAF Flight Dynamics Laboratory that were performed using in-flight simulators or variable stability aircraft. These experiments have produced a valuable data base and tentative requirements applicable to highly augmented aircraft, but this work has not yet been reflected in the military flying qualities specification. There is in general a lack of appreciation in the design community for the degree of sensitivity of the pilot-aircraft closed-loop system to time delay or incremental phase shift introduced by augmentation systems, prefilter models and digital equipment. Paper No. 22 documents one example where these effects resulted in degraded flying qualities when the augmentation system was turned ON.

Paper No. 22 also reports roll attitude oscillations were experienced in landing which were the result of high roll acceleration command authority. This problem has also been experienced in US designs, for example, the YF-16 roll control gain initially proposed for the airplane was found, through in-flight simulation and flight test, to be much too high and was reduced. It is possible that the roll performance requirements of MIL-F-8785B tend to cause designers to build aircraft with roll sensitivity that is too high, however, in most modern aircraft developments the designer makes use of ground simulation trials and it is believed by the author of this T.E.R. that limited motion ground simulators tend to cause pilots to select control gains that are much too sensitive in flight. It should be noted that the author of paper No. 22 stated that the pitch PIO encountered in flight could only be found after the fact in the ground

simulator by using an unrealistic technique to deliberately induce the problem.

Paper No. 24 was presented after No. 22 so that Paper No. 23 could be presented last in the session. Paper No. 24 reports on a ground simulation experiment in which an extensively augmented airplane was evaluated for approach and landing. The test results indicate that the visual flare and landing were the most critical parts of the task. The pilots had no trouble adapting to the side stick although the trigradient roll command was essential for the side stick. Although the augmented airplane is a higher order system including a prefilter, proportional plus integral command paths and attitude stabilization, the authors reported that the flying qualities evaluation ratings for the configurations for which the equivalent short period frequency was varied were consistent with the MIL-F-8785B requirements when lower order "equivalent system" parameters were used to describe the configurations.

There were only a few configurations evaluated with the spoiler being commanded by the pitch stick through a washout filter, but these evaluations did tend to indicate an improvement in the flying qualities. It is not clear from the written paper or the presentation as to whether or not these configurations could be correlated by lower order equivalent systems or by parameters in the Neal-Smith closed-loop criteria.

In paper No. 23 the representative from the U.S. Naval Air Systems Command and the representatives from McDonnell-Douglas at St. Louis took the position that the requirements in MIL-F-8785B can be applied to augmented aircraft if the characteristics of these aircraft are properly represented by a lower order equivalent system. Examples of this philosophy are presented for the longitudinal requirement on short period frequency as a function of n_z/α and the requirement limiting control system phase lag at the short period frequency. It is advocated that the pitch attitude to stick force transfer function for the higher order system be fit (amplitude ratio and phase angle as a function frequency) by a lower order transfer function of the following form:

$$\frac{\theta}{F_s}(s) = \frac{K \left[s + \left(\frac{1}{T_{\theta 2}} \right)_e \right] e^{-\tau_e s}}{s \left[s^2 + 2 \zeta_e \omega_{n_e} s + \omega_{n_e}^2 \right]}$$

where:

$$(n_z/\alpha)_e = \left(\frac{1}{T_{\theta 2}} \right)_e \frac{V_T}{g} \quad \text{and} \quad \left[\begin{array}{c} \text{Control System} \\ \text{Phase Angle} \end{array} \right] = 57.3 \zeta_e \omega_{n_e}$$

$$\omega = \omega_{n_e}$$

The authors of paper No. 23 claim that these equivalent system parameters can be used with the requirements in MIL-F-8785B to determine the acceptability of a proposed design. The authors advocate letting all parameters in the lower order transfer function vary when the equivalent match is calculated. This process may result in values of $\left(\frac{1}{T_{\theta 2}} \right)_e$ that are significantly different from the heave damping parameter L_α or $-Z_w$. Using this value of $\left(\frac{1}{T_{\theta 2}} \right)_e$ to calculate $(n_z/\alpha)_e$ will then result in values of $(n_z/\alpha)_e$ that are different from the value that would be measured in a wind tunnel test. This aspect of the equivalent system method proposed in paper No. 23 caused some members of the audience to reject the approach on the basis that the equivalent parameters appear to no longer have any physical significance.

It is the opinion of the author of this T.E.R. that the "equivalent system" approach proposed by paper No. 23 is much preferred to the "dominant root" method used by some organizations when comparing augmented aircraft with the specification. It is, therefore, recommended that the equivalent system procedure advocated in paper No. 23 be adopted as the official procedure for application of MIL-F-8785B to highly augmented aircraft. This procedure is recommended as an interim measure to be used until a generalized revision is developed.

Paper No. 23 contains a discussion concerning whether $\frac{1}{T_{\theta 2}}$ or $n_z/\alpha = \frac{V}{g} \frac{1}{T_{\theta 2}}$ should be used as a correlating parameter for longitudinal short period frequency. The authors of paper No. 23 are of the opinion that $\frac{1}{T_{\theta 2}}$ is the better parameter and they cite data and published documents that they claim lend support to this position. One of the documents they cite is the July 1968 Draft Specification MIL-F-8785A which they claim presented short period frequency requirements as a function of $\frac{1}{T_{\theta 2}}$. This is not true. The requirement in that document was stated in terms of n_z/α in the same format as is used in MIL-F-8785B.

2.6 The Participation of the Pilot

Three papers were presented in this session, two of which discussed sophisticated mathematical models of the pilot that include modeling of the pilot's information-gathering and decision-making processes. Paper No. 25 was based on optimal control concepts. In paper No. 26, the pilot is modeled as a discrete-time process where decision-making has a sequential nature. It is also assumed that the pilot's objectives are better formulated as a measure of the closeness with which the aircraft follows a reference trajectory than as a quadratic cost functional as is used in the optimal control concept. The work of paper No. 26 is similar to work performed by Onstott of Northrop under USAF AFFDL sponsorship but the author does not reference Onstott's work.

The concept of the pilot performing as a sequential process evoked much comment and discussion from the audience with several people challenging the sequential concept. A primary reason for modeling the

pilot this way was that it permits accounting for failure of the pilot to handle the workload in certain circumstances.

Paper No. 27 described curved decelerating approaches to landing performed in the augmentor wing powered-lift STOL aircraft. The aircraft was operated on the "backside" of the power curve and had available redundant controls. To relieve the pilot workload, separate stability augmentation for attitude and speed was provided as well as a supporting flight director and special electronic displays. This experiment demonstrates the feasibility of performing curved decelerating approaches in simulated instrument conditions when adequate navigation, profile computation, control authority, and cockpit displays are available.

2.7 Round Table Discussion — Problems that May Impede Full Implementation of ACT

The round table discussion was chaired by Professor R. S. Shevell, Stanford University. The six panel members were:

D. Lean, Superintendent, Flight Dynamics Division, RAE
J. Hodgkinson, Lead Engineer, Aerodynamics, McDonnell Aircraft
W. T. Hamilton, V. P. Research and Engineering, Boeing Aerospace Co.
J. Czinczenheim, Societe Avions Marcel Dassault-Brequet Aviation
K. H. Doetsch, Professor Tech. University Braunschweig
H. A. Mooij, Head Stability and Control Dept., NLR

Each panel member made a three-minute statement, in turn, after which the audience participated in the discussion. Summaries of the initial statements of the panel members follow.

Mr. Lean

There are many factors to impede implementation of ACT. There are a variety of characteristics that could be implemented but only a few are really useful. Cost and reliability are the main impeding factors. ACT impinges on performance and peace of mind. Some functions give only pilot ratings, some seem intuitively good but are they? The benefits of active flutter and maneuver load control can be calculated while other functions are included to make the pilot's job easier. But do they really result in improvement? Maneuver limiting should result in fewer accidents but costs, complexity increase. But will it make us more effective in combat? We don't have information now. We must build demonstration aircraft to prove the value of ACT and CCV.

Mr. Hodgkinson

Flying qualities are being attacked by each designer. Why not some centralized research on ACT and flying qualities. We need some lead time on problems and should not have to solve problems after design deficiencies have been found. Need generalized, systematic, planned research and freely disseminated results.

Mr. Hamilton

The technology is in hand or being developed. The primary design modes are being identified, e.g., relaxed stability results in less trim drag, reduced weight and increased performance. The secondary design aspects are not being properly recognized — design for safety and forgiveness during gusts, pilot errors, emergency actions, ground effect, rotate to take off, taxi on ice with one engine out requires weight on nose wheel, rudder size fixed by taxi requirement. ACT using high performance, full authority control system will require thorough aerodynamic, structural, electrical and hydraulic math models of the aircraft and its control system. Attention must also be paid to the loads in servo mounts. More design iteration will be required, time and cost involved. Must have payoff to make worthwhile.

Mr. Czinczenheim

New operational modes are possible. Insensitive systems could be made which reduce need to know accurately the airplane characteristics. Need good flying qualities at high angle of attack. Airplanes can carry a great variety of external loads. Need knowledge of characteristics at high α and β for external loads. Need to measure unsteady effects early in study. All this causes long studies and more difficulty. How to get the needed data is a problem. In the meantime, one way is to adopt adequate margins from ultimates. Choose flexible solutions that can be adjusted later. Aero data in more detail is required from the beginning for use in stability, flying qualities, mission simulation and maneuvers. Other papers have highlighted new analysis methods for describing nonlinear characteristics at high angle of attack. Must continue these efforts.

Professor Doetsch

In 1961 at the first stability and control meeting of the FMP, a paper warned against use of black boxes. Now we have similar situation. Don't rush too quick to ACT, other ways are available to solve problems that are more sure and safe. Not sure systems satisfy me as a pilot. Relying on statistical safety is a worry. I would like proof of safety. Not safety through redundancy. This is the modern "wave". We had self-adaptive control, autostabilization, now CCV. Maybe it will pass too. I would like to make three points: 1) Before we modify aircraft handling, we must know what is required in terms of aerodynamic force and moments. 2) Does the human operator fit into the new environment or do we have to train for new systems. Dog-fighting is no longer involved in war, for example. 3) Hasten to adopt flying qualities requirements.

Mr. Mooij

In the transport field, the SST will need ACT. Boeing has solved the redundancy problem by using a

"Hard SAS". The Concorde test aircraft with FBW has no fundamental flying qualities problems. In the case of subsonic transports, the question is more subtle. For a 3-5% L/D improvement, it is not clear it will pay for a system. In turbulence, the flying qualities can be enhanced by ACT and this is a good prospect. The area of flying qualities criteria needs attention in the following areas. Trend toward higher wing loading requires more research for low n_z/a . DLC also needs study. We should stress the need for more in-flight simulation and the inclusion of flare and touchdown in the evaluation task. We should get away from the ground simulator fixation.

Major Points Raised by Audience:

The following is a summary of the major points discussed during the second part of the round table which involved audience participation.

A common thread in previous discussion and presentations was that there was a need for demonstration of cost effectiveness of ACT. The question was asked, how should this be done? The answers ranged from suggestions to add features in small steps, to let the competitive pressures of the commercial market drive it, to some applications are so expensive and high risk in a financial sense that only governments can address. Also some payoffs are difficult to quantify such as passenger comfort. Cost effectiveness analysis is very complex and the answers can be driven by the starting assumptions.

It was noted that the new 767 does not incorporate ACT and the question was asked what did Boeing do to decide not to include ACT concepts. It was stated that Boeing emphasized noise and fuel economy in 767. A study had been made of potential for maneuver load alleviation on the 747 which indicated such a design would require much more design work and cost and they would end up with a very restricted solution. Instead, Boeing designs the wing, builds it, tests it to destruction and then beefs it up. They can then put higher thrust engines on the wing and carry more weight to get growth versions of the airplane. The process saves lots of design effort and manufacturing methods and parts are common. If ACT was used they would be stuck with a specific wing design and would have a big redesign problem for growth versions. NASA-sponsored research is used by Boeing to satisfy customer requirements but may not be directly applied.

The question of risk of design errors and the state of knowledge about lightning strike effects on active control systems was raised. The use of fiber optics was mentioned together with shielded wires and in the case of composite structures to build screens into the structure to carry the current. Computers might be made immune if you make sure your data is created fresh, i.e., not rely on stored data in the computer. It was suggested that the Avionics or Electromagnetic Wave Propagation Panels be asked to consider the lightning strike problem.

Reference was made to a study being funded by NASA to explore the design implications of ACT and CCV. The impression given by advocates seems to be that ACT saves weight and drag and nothing bad happens. The referenced study shows, however, that in the real design process, there are many implications to the overall design. Every system added costs and adds weight. When adding a wing load alleviation system, new problems were encountered that restricted feasibility by causing weight growth in actuators, fatigue weak points, required complex studies and caused worry about the cost to certify the system. Also, it is necessary to consider the impact on already certified systems. Many modes of operation and failure states must be considered which gets costly. Actually, the structure is the cheap part of the airplane; the costly parts are the type things necessary for ACT. Also the maintenance required by operators such as airlines is a costly factor.

A similar experience was cited in the Boeing SST design. Studies indicated a flutter problem which would require 6000 lb of structure to fix. Preliminary look at an active flutter control system indicated a system weighing 2600 lb. As detail design progressed, the weight and complexity grew until soon the weight saving had vanished so the idea was dropped in favor of simple structure.

It was suggested that a shortage of qualified mechanics in the military services who are qualified to maintain complex mechanical flight control systems might be a force in favor of fly-by-wire systems. It was pointed out that the F-18 has both systems. In the helicopter field, it is hoped that fly-by-wire systems will permit eliminating complex mechanical hardware.

Although the panel was intended to address "Problems that may impede full implementation of ACT", the thought was expressed part way through the discussion that too much attention was being given by the group to negative aspects of ACT. In this vein it was noted that active control technology was progressing rapidly and will be used if performance justifies it.

It was noted that a control configured vehicle does not necessarily have to use active controls. The B-52 airplane was cited as an example. It has many design features to minimize control authority required. It was designed for only one engine of eight failed at a time, it has crosswind landing gear, the gear is bicycle design and the airplane is not rotated for takeoff, and the bomb bay is on the c.g.. It has a trimmable stabilizer with small elevator and rudder. These design features were necessary at the time and that is what always drives the situation.

The large advantages of relaxed static stability and active controls were cited for the delta wing fighter. It was pointed out that the primary problem that inhibited the flying wing concept, i.e. stability, can be solved by active control.

Concern was expressed by pilots that additional control modes might further complicate the cockpit environment.

The US representative from the USAF AFMAL stated that he had hoped for a consensus on issues that would help decide where to apply limited funds.

- Improve technology
- Demonstration aircraft
- Operational trials
- Flying qualities criteria

The question is what are the real concerns or hangups that could benefit from government support?

The opinion was expressed that ACT may be a solution looking for a problem. The required technology is developed and now ACT should be left to the exploiters, we should let the designers make use of ACT if they find it to be an advantage.

This opinion was challenged and the opposite view was expressed that there are technical areas that need improvement and because uncertainties exist on payoff, there is a need to do technical work and to educate people and try to apply the technology. This view was moderated by the observation that when technology arrives at a certain point, it gets used without a push. The yaw damper solved a problem and was cheap so it has been adopted. Auto flap retraction works and is being used partly because the consequences of failures are minor. If ACT concepts make it easier to fly, they will be adopted but complicated decoupled systems may not be desirable.

It was pointed out that military aircraft are a more difficult case because experience shows you never do the mission you design for so ACT must provide broad advantages that can meet a variety of needs. Need operational demonstration to prove the benefits.

3. CONCLUSIONS

The following conclusions are drawn from the information presented at the symposium.

General Conclusions

- The technology exists to permit application of CCV and active control concepts to operational aircraft.
- Questions remain concerning the operational need and the cost effectiveness of many of the concepts that are technically feasible.
- Cost, reliability and maintainability are the main factors impeding implementation of ACT.

Specific Conclusions

- Realization of performance and operational gains offered by ACT will require departure from existing design practice.
- Overall success of ACT depends on ability to handle failure modes and to provide cost effective reliability and maintainability.
- The use of ACT to reduce dynamic structural loads and to stabilize structural modes will involve unprecedented understanding of aerodynamic and structural characteristics, control system responses and compatibility problems and will require advances in our ability to describe and model such phenomena.
- Work remains to be done before structural dynamic and aerodynamic models can be used with confidence in the initial CCV configuration selection.
- Emphasis should be given to development of control approaches that are parameter-insensitive which can deal with errors in predicted aircraft parameters.
- Aerodynamic forces and moments at high angle of attack and sideslip are affected by flow separation and exhibit nonlinearities and discontinuities which are very configuration-sensitive.
- Interference effects of captive model support structures can become large at high angle of attack.
- There are many problem areas involved in high angle of attack wind tunnel testing that require further development.
- Application of ACT to aircraft design must consider problems in three frequency ranges.
 - "Low frequency" range - Rigid body motions and flying qualities.
 - "Mid-Frequency" range - Maneuver loads, gust loads, aerodynamic buffet and ride qualities.
 - "High-frequency" range - stabilization of structural modes and active flutter control.
- The missile designers have been dealing with many of the active control design problems now worrying aircraft designers and much of the missile experience is applicable to the aircraft design application.
- The requirements for safety, reliability and life cycle cost are significantly different for manned aircraft than for missiles. These factors may have a dominant influence in determining the role of ACT in future aircraft design.
- Design studies indicate the CCV concept of negative static stability and the use of full authority active controls to provide dynamic stability and departure prevention can provide large

improvements in performance of fighter aircraft.

- Use of full authority active controls to stabilize a statically unstable airframe requires high reliability in the flight control system.
- The current approach to reliability is through redundancy and redundancy management using digital computer technology.
- When dependence is placed on active controls for basic stability it is imperative that adequate control power, surface rate, hinge moment capability and dynamic bandwidth be provided to handle all circumstances.
- Experience with "side stick" controllers indicates it is not critical whether the controller is located on the right hand side, left hand side or in the center of the cockpit.
- "Side Stick" controllers should have stick motion. Multi-gradient command gain in roll is essential.
- The dynamic behavior of airplanes at high angle of attack, such as wing rock, can be calculated using stability derivatives that are nonlinear functions of roll rate, sideslip and angle of attack.
- Random fluctuation of rolling and yawing moments resulting from flow separation at high angle of attack must be accounted for in analysis and simulation.
- Discrete gust models may be more useful than power spectral density models for analysis of the effects of low altitude wind and turbulence effects on automatic and manned landing performance.
- Flight test demonstration projects permit acquisition of hands-on experience and the development of analysis and design methods.
- Flight test demonstration projects develop confidence in and promote acceptance of new concepts.
- The effect of lightning strikes on digital flight control systems carried in aircraft with composite structural material is poorly known.
- It is important to differentiate between statically stable and statically unstable aircraft in reliability analysis.
- Dynamic testing in wind tunnels capable of generating controlled gust environments is an effective way to develop active control systems.
- The language used to state flight control system reliability requirements may dictate redundancy. For example, "Two fail operational".
- Flight tests have demonstrated that direct force control can be used to advantage. Examples are the use of side force in ground attack and in crosswind landings.
- Test bed aircraft suitable for demonstration of feasibility may not be adequate to evaluate cost effectiveness for operational use.
- Control surfaces used to decouple aircraft motions and implement CCV concepts can exhibit nonlinearities and interference effects which must be considered in the design process.
- Interactions between the force and moment producers on a CCV design can be prime factors in determining the viability of unconventional control modes.
- Future CCV designs may require an increased scope of wind tunnel testing to identify and solve adverse aerodynamic interaction and nonlinear effects.
- Guidelines are needed to define acceptable levels of buffet and energy changes associated with decoupled control modes.
- An urgent need exists for development of appropriate flying qualities criteria for decoupled control modes and control modes using direct force controls.
- The best way to command unconventional control modes has not been resolved but appears to be task specific.
- Direct side force control has been shown to be advantageous during crosswind landing, however, practical means for generating the side force are lacking.
- Ability to demand a certain pitch acceleration for stall recovery may be an important design requirement for establishing aft c.g. limits and tail sizes in relaxed static stability designs.
- The philosophy and requirements for civil certification of active control systems must be defined. Reliance on probabilistic analysis may be necessary.
- Recent aircraft using high-authority, fly-by-wire augmentation systems have been initially found to have unacceptable and dangerous flying qualities. Examples are YF-17, YF-16, Tornado and Space Shuttle.

- Control system lags and time delays introduced by prefilter models, augmentation systems and digital equipment can severely limit the pilot-airplane closed-loop dynamic bandwidth causing "pilot-induced oscillations" when dynamically demanding tasks are attempted.
- The flying qualities requirements of MIL-F-8785B need updating to better handle aircraft with higher order transfer functions and aircraft incorporating direct force control.
- The "equivalent lower order system" method is much preferred over the "dominant root" method for applying the dynamic requirements of MIL-F-8785B to aircraft with higher order transfer functions.
- Progress is being made in attempts to model the pilot's information-gathering and decision-making processes, however, a generally accepted form for the model has not yet evolved.
- Cost and reliability are the main factors impeding implementation of ACT.
- Demonstration aircraft must be built and evaluated to determine the value of various ACT and CCV concepts.
- Secondary design requirements must be given proper attention in evaluation of ACT and CCV potential.
- The need for more in-flight simulation should be stressed with less fixation on the use of ground simulators.
- Some ACT applications replace simple, inexpensive structure with complex, expensive and difficult to maintain hardware.

4. RECOMMENDATIONS

Recommendations worthy of consideration for action that can be taken by: AGARD through its Panels; the North Atlantic Military Committee; the National Authorities of the individual member nations of NATO are listed below.

- Considerable work needs to be done before structural dynamic and aerodynamic models can be used with confidence in the initial CCV configuration selection.
- Considerable work needs to be done to develop flying qualities criteria for airplanes with higher order transfer functions and for aircraft using direct force control.
- Wind tunnel methods for testing models at high angle of attack require improvement.
- Design studies, simulation studies, demonstration flight vehicles and operational test and evaluation are required to define the operational value and cost effectiveness of ACT and CCV concepts.
- Efforts to reduce cost and increase reliability of active control systems should be encouraged and supported.
- Emphasis should be given to development of systems that are parameter insensitive which can deal with errors in predicted aircraft parameters.
- Better models of atmospheric disturbances at low altitude should be developed. In particular, in the low-frequency range (windshear).
- The effects of lightning strikes on digital flight control systems should be determined.
- The philosophy and requirements for civil certification of active control systems and control configured vehicles must be defined.

REFERENCE

1. Whitmoyer, Robert A.: "Aerodynamic Interactions on the Fighter CCV Test Aircraft," Paper No. 16, AGARD Conference on Dynamic Stability Parameters, Athens, Greece, May 1978.

APPENDIX 1

LIST OF PAPERS

Session I - Summary of Recent Experiences in Stability and Control

1. "Systems Implications of Active Controls"
P. R. Kurzahls, NASA, USA
2. "Dynamic Stability Parameters" (Summary Paper on a Fluid Dynamics Panel Symposium)
L. E. Ericsson, Lockheed, USA
3. "Structural Aspects of Active Controls" (Summary Paper on a Structures and Materials Panel Symposium)
R. Destuynder, ONERA, France
4. "Control of Missile Airframes (Review of the S & C Aspects of Missiles)
D. J. Frary, BAC, UK

Session II - Application of Active Controls to Specific Aircraft and Aircraft Configurations

5. "Enhanced Fighter Mission Effectiveness by Use of Integrated Flight Systems"
J. H. Watson and W. S. Bennett, General Dynamics, USA
6. "Experimental Study on a Simulator and in Flight of a Fly-by-Wire System Used for Longitudinal Relaxed Stability Applied to Concorde"
A. Cazenave and J. Irvoas, SNIAS, France
7. "Improvement of Fighter Aircraft Maneuverability Through the Employment of Control Configured Vehicle Technology"
J. Stalony-Dobrzanski and N. Shah, Northrop, USA

Session III - General Problems Concerning Stability and Control and Associated Mathematical Models

10. "Lateral Stability at High Angles of Attack"
A. J. Ross, RAE, UK
11. "Stall Behavior Evaluation from Flight Test Results"
H. Wuennenberg, Dornier and G. Sachs, Bundeswehr-Hochschule, Munchen, FRG
12. "Hybrid Computer Investigation of Discrete Gust and Windshear Effects on Automatic Landing System Performance"
K. W. Rosenberg, Marconi Elliot, UK
13. "Aircraft Response to Windshears and Downdraughts"
J. C. van der Vaart, DUT, NL
14. "Gust Alleviator - Feasibility Study for G91Y - Tactical Light Fighter"
R. Carabelli, Aeritalia, IT
15. "Design Considerations for Reliable FBW Flight Control"
James K. Ramage and James W. Morris, Air Force Flight Dynamics Laboratory
16. "Open/Closed Loop Identification of Stability and Control Characteristics of Combat Aircraft" (NATO restricted)
R. Koehler and M. Marchand, DFVLR, FRG
- 16a. "Dynamic Wind Tunnel Simulation of Active Control Systems"
Dr.-Ing S. M. Peter Hamel and B. Krag, DFVLR

Session IV - Results Obtained with CCV's

17. "Stability and Control Aspects of the CCV F104G"
G. Loebert, U. Korte and H. Beh, MBB, FRG
18. "Design Guidance from Fighter CCV Flight Evaluations"
F. R. Swortzel, AFFDL, USA and J. D. McAllister, General Dynamics, USA
19. "Use of Direct Forces - Predictions and Flight Tests on a Light 6 Axes Variable Stability Aircraft of Princeton University"
C. La Burthe, ONERA and J. P. Petit and A. Guillard, CEV, France
20. "L-1011 Active Control Design Philosophy and Experience"
D. M. Urie, Lockheed, USA
21. "In-Flight Handling Qualities Investigation of Various Longitudinal Short Term Dynamics and Direct Lift Control Combinations for Flight Path Tracking Using the DFVLR HFB 320 Variable Stability Aircraft"
D. Hanke and H. H. Lange, DFVLR, FRG

Session V - Criteria for Satisfactory Behavior of Aircraft With Advanced Stability and Control Systems

22. "Handling Qualities Requirements and the Fly-by-Wire Aeroplane"
J. C. Gibson, BAC, UK
23. "Are Today's Specifications Appropriate for Tomorrow's Aeroplanes"
R. C. A'Harrar, NASC, J. Hodgkinson, and W. J. LaManna, McDonnell, USA
24. "Simulator Investigation of Handling Qualities Criteria for CCV Transport Aircraft"
H. A. Mooij, W. P. deBoer and M.F.C. van Gool, NLR, NL

Session VI - The Participation of the Pilot

25. "Mathematical Models of Manned Aerospace Systems"
P. H. Wewerinke and J.J.P. Moelker, NLR, NL
26. "The ONERA Discrete-Time Pilot Model"
D. Cavalli, ONERA, France
27. "Flight Experiments with Advanced Controls and Displays During Piloted Curved Decelerating Approaches in a Powered Lift STOL Aircraft"
W. S. Hindson, NAE, Ottawa, Canada - G. H. Hardy, NASA Ames, USA

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